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FRACTURE DAMAGE AND FAILURE OF CANNON COMPONENTS BY SERVICE LOADING

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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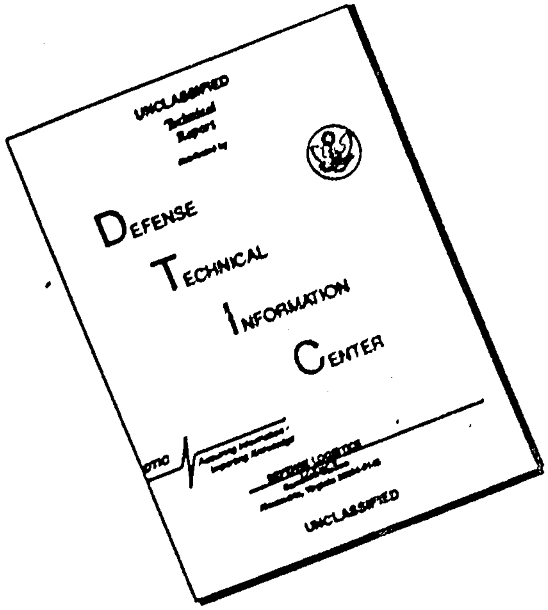

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The types of crack-related failure which occur as a result of cannon firing are reviewed. A very severe brittle fracture of an early cannon is resummarized. The failure processes typical of cannons are described, including crack initiation due primarily to high temperature exposure, fatigue crack growth due to the cyclic pressurization of firing, and final fast fracture through the wall of the cannon tube. The effects of chemical environment and residual stresses on the failure processes are discussed.

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INTRODUCTION

The major structural components of a cannon are subjected to quite severe service conditions including applied stresses which approach the material yield strength, high temperature exposure, and aggressive chemical environments. Because there are limitations on the size and weight of a cannon, it is not possible to simply increase the section size of a cannon in order to minimize the effects of the service conditions. As with many highly stressed structural components, the tendency has been to increase the strength of cannon materials in response to the conflict between service conditions and weight limitations. This increase in strength has resulted in a related increase in concern for crack-related fracture of cannons. Quite naturally, high strength materials are highly stressed, and unfortunately they are less tolerant of cracks than low strength materials. This combination results in a greatly increased likelihood of fracture compared with with that for low strength materials. The purpose of this report is to review the damage and failures which can occur in cannons with emphasis on the types of crack-related fracture which seriously affect the function and service life of cannons.

The review will be in two parts. First, a brief description is given of a very severe type of damage and failure which can occur in incorrectly designed cannons; that is, a brittle, fragmentation-type failure of a cannon made from a steel with too low a value of fracture toughness. Second, a typical progression of crack-related fracture in a cannon is described. This includes crack initiation at the inner radius of a cannon tube, fatigue crack growth in the tube wall, and the final fast failure through to the outer radius of the cylinder.

BRITTLE FAILURE

A failure of an Army cannon occurred in 1966 which, based on an extensive investigation, proved to be a classic brittle fracture as the result of normal service conditions. Details of the failure and the redesign of the cannon have been described elsewhere.[1,2] The brief review here is intended to describe the extreme situation of very severe damage and failure of a cannon. In fact, this failure led to many fracture-safe design procedures now used for cannons.

Figure 1. Early brittle failure of 175 mm inner diameter Army cannon.

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[1]Davidson, T. E., Throop, J. F., and Underwood, J. H., "Failure of a 175 mm Cannon Tube and the Resolution of the Problem Using an Autofrettaged Design," Case Studies in Fracture Mechanics, T. O. Rich and D. H. Cartwright, Eds. AMMRC MS 77-5, Army Materials and Mechanics Research Center, 1977.

[2]Underwood, J. H. and Kendall, D. P., "Fracture Analysis of Thick-Wall Cylinder Pressure Vessels," ARLCB-TR-82007, ARRADCOM, Benet Weapons Laboratory, Watervliet, NY, April 1982.

The photograph in Figure 1 gives a good description of the serious, fragmentation nature of the failure. Many fragments and the remaining breech end of the 175 mm cannon tube are shown. Careful examination of the fracture surfaces determined that the origin of the fragmentation-type failure was a semi-elliptically shaped fatigue crack from the inner radius of the tube with a depth of $a = 9.4$ mm into the tube wall (in the radial direction) and a length of $2c = 28$ mm along the inner radius (in the axial direction). Using this critical crack size information along with the cannon firing pressure and geometry and fracture mechanics solutions from the literature, the applied stress intensity factor at failure can be calculated. Comparison of the applied stress intensity factor with the measured critical stress intensity factor for the material, that is, the plane strain fracture toughness, is the accepted method for describing and predicting the conditions for brittle fracture. This comparison, for the 175 mm tube which failed, can be made from Eqs. (1) and (2) below. First,

$$K_{applied} = 2.70\ f_s\ p(\ a)^{1/2} = 112\ \text{MPa(m)}^{1/2} \qquad (1)$$

In Eq. (1) the constant 2.70 is from the K solution[3] for a 9.4 mm deep crack in a pressurized cylinder with 178 mm inner radius and 373 mm outer radius. The factor $f_s = 0.70$[4] accounts for the fact that the crack is semi-elliptical in shape rather than straight-fronted as required in the K solution,[3] p is the

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[3]Bowie, O. L. and Freese, C. E., "Elastic Analysis For a Radial Crack in a Circular Ring," Engineering Fracture Mechanics, Vol. 4, No. 2, June 1972, pp. 315-321.

[4]Newman, J. C. and Raju, I. S., "Analysis of Surface Cracks in Finite Plate Under Tension or Bending Loads," NASA TP 1578, National Aeronautics and Space Administration, 1979.

firing pressure of the cannon, 345 MPa, and a is the 9.4 mm crack depth. This gives the value of $K_{applied}$ indicated, 112 $MPa(m)^{1/2}$. Comparing this with

$$K_{material} = K_{Ic} = 90 \ MPa(m)^{1/2} \tag{2}$$

indicates that a failure would be expected because $K_{applied}$ is considerably above K_{Ic}. There are other requisites for a brittle failure, such as a large enough section size in the component so that the plane strain constraint can be maintained at the crack tip. But the basic requirement is that $K_{applied}$ exceed K_{Ic}. Since this was clearly the case, the redesign of the gun tube focused on increasing the material fracture toughness, K_{Ic}.

The basic change required in the redesigned tube was dictated by test results such as those shown in Figure 2. This plot, from recent work,[5] shows the consistent decrease in fracture toughness which is observed in structural materials as the yield strength is increased. The results in Figure 2 are from a number of gun tube forgings which had been quenched and tempered to different yield strengths from about 1100 to 1300 MPa. This same effect is observed for nearly all structural alloys, that is, a decreasing toughness with increasing strength. Thus, the maximum allowed yield strength for the 175 mm tube was decreased from 1310 to 1100 MPa, resulting in a significant increase in expected fracture toughness. The data in Figure 2, obtained from recent gun tube forgings, correspond to an increase in average (linear regression line) toughness from about 128 to 185 MPa. These values include no testing variation or tube-to-tube variation, but they do show the significant

[5]Underwood, J. H., "The Equivalence of K_{Ic} and J_{Ic} Fracture-Toughness Measurements in Ni-Cr-Mo Steels," Experimental Mechanics, Vol. 18, No. 9, September 1978, pp. 350-355.

increase in toughness which can be accomplished by reducing the yield strength.

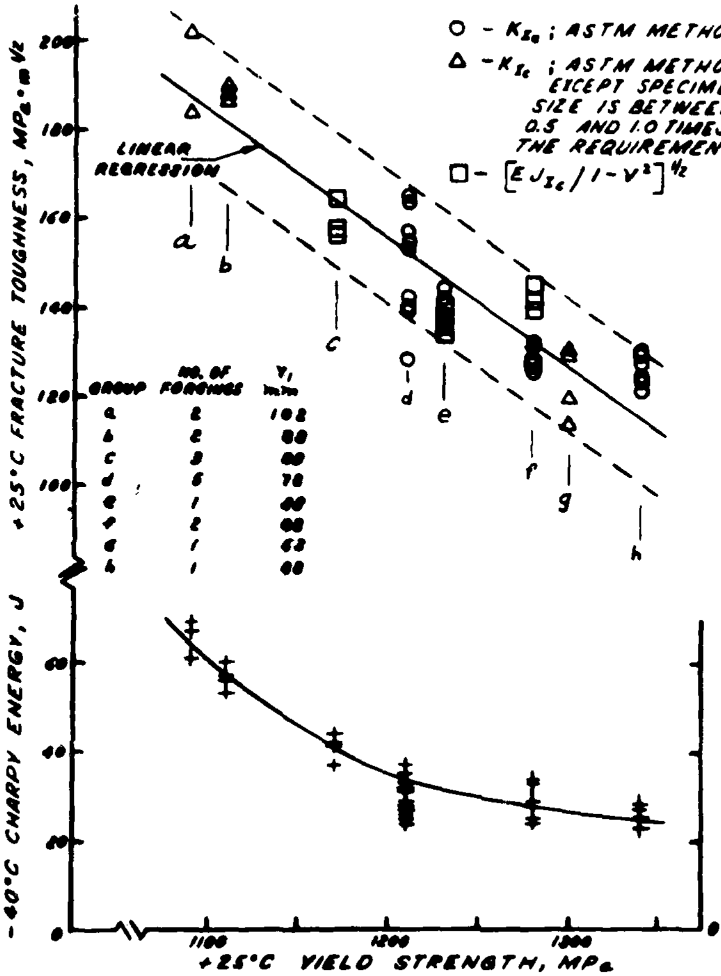

Figure 2. Fracture toughness and Charpy energy versus yield strength for ASTM A723 cannon forgings; from Reference 5.

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[5]Underwood, J. H., "The Equivalence of K_{Ic} and J_{Ic} Fracture-Toughness Measurements in Ni-Cr-Mo Steels," Experimental Mechanics, Vol. 18, No. 9, September 1978, pp. 350-355.

A second important change in the redesigned tube was from an air-melted to a vacuum-melted steel. In Figure 2, for a strength of 180 MPa, that of the failed tube, the lower bound of fracture toughness is about 140 $MPa(m)^{1/2}$. This value and all data in Figure 2 is from vacuum processed gun steel. From Eq. (2) above, the measured K_{Ic} from the failed tube was 90 $MPa(m)^{1/2}$*. This difference is attributed to air versus vacuum melting of the steel. In the ASTM specification[6] for high strength pressure components, which is now used for gun tube forgings, a vacuum treatment of the steel is required.

The brittle failure which occurred during firing of the 175 mm gun tube has been intentionally duplicated in laboratory and controlled field testing of tubes with similar, low fracture toughness. In more recent 175 mm and other size gun tubes which have incorporated the lower strength, higher toughness, vacuum treated steel described above, there was no indication of a brittle, fragmentation-type failure. A material fracture toughness, K_{Ic}, in excess of applied stress intensity factor, $K_{applied}$, has become an absolute requirement in gun tube design, in order to avoid brittle fracture during service.

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[6]Standard Specification for Alloy Steel Forgings for High-Strength Pressure Component Application, ASTM A723-80, Annual Book of ASTM Standards, Part 4, American Society for Testing and Materials, 1982, pp. 791-797.

*This value should be considered a lower bound, for comparison with the lower bound from Figure 2, because it was from the one tube which failed out of a large population.

TYPICAL DAMAGE

Careful analysis of a fracture surface of a cannon tube can reveal the typical damage and failure processes which occur during service loading. Figure 3 is a photo of a tube fracture surface[7] with a small portion of the inner radius included at the bottom of the photo. The area of fracture surface shown is about 70 mm, the tube wall thickness, by about 250 mm. This fracture surface shows quite graphically the service damage that can occur. It is convenient to categorize the damage into three types, crack initiation, fatigue crack growth, fast crack growth. Before discussing these categories, one other important aspect of service damage must be discussed, since it can significantly affect or even control all of the damage processes in a cannon. This is the effect of chemical environment. As one important example, it is known that hydrogen sulfide, H_2S, is present in many cannon firing products. Fruther, H_2S has been identified in the work of Clark[8] and others as a very aggressive environment for high strength steels of the type used for gun tubes. Each of the three types of damage mentioned above can be greatly accelerated by H_2S. Since it is the inner radius of the tube which is exposed to H_2S, the initiation and early fatigue crack growth could be the most

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[7]Underwood, J. H. and Throop, J. F., "Surface Crack K-Estimates and Fatigue Life Calculations in Cannon Tubes," Part-Through Crack Fatigue Life Prediction, ASTM STP 687, J. B. Chang, Ed., American Society for Testing and Materials, 1979, pp. 195-210.

[8]Clark, W. G., Jr., "Stress-Corrosion Crack Initiation in High-Strength Type 4340 Steel," Flaw Growth and Fracture, ASTM STP 631, American Society for Testing and Materials, 1977, pp. 121-138.

affected, and these shallow crack damage processes* account for most of the service life of a cannon tube, so environmentally assisted or controlled damage of cannon components must be considered. Fortunately, there is no sustained tensile service loading at the inner radius of a cannon tube, so that environmentally assisted crack growth is seldom observed. The time duration of tensile loading during firing is so small that environmentally assisted fracture rarely occurs.

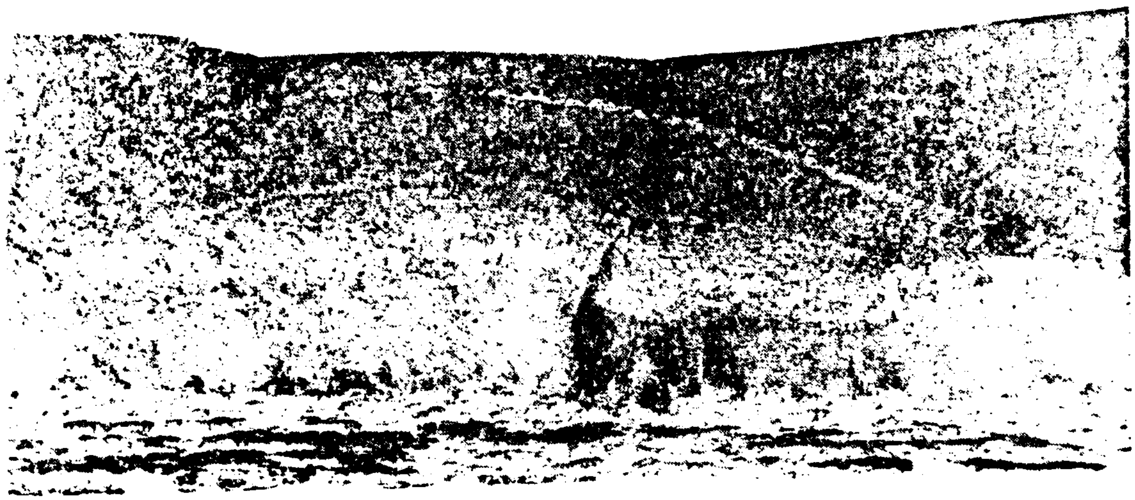

Figure 3. Fracture surface of cannon tube after fatigue failure; A723 steel, 1200 MPa yield strength, 60 mm inner radius, 130 mm outer radius; from Reference 7.

[7]Underwood, J. H. and Throop, J. F., "Surface Crack K-Estimates and Fatigue Life Calculations in Cannon Tubes," Part-Through Crack Fatigue Life Prediction, ASTM STP 687, J. B. Chang, Ed., American Society for Testing and Materials, 1979, pp. 195-210.

*Early fatigue crack growth is believed to have the most effect on service life of cannons.

Crack Initiation

Referring again to Figure 3, a section of the inner radius of the cannon tube can be seen at the bottom of the photo. For this particular tube, a relatively severe heat checking and erosion process has occurred; the dark areas oriented in the horizontal direction in the photo* are eroded areas several millimeters in depth. More typical in tubes with lower firing temperatures at the inner radius would be heat-check cracking of up to 1 mm in depth. Both the severe and the more typical shallower damage are due to the thermal and transformational stresses associated with the temperature cycling at the inner radius. The damage occurs within a few tens or hundreds of cycles, so compared with the many thousands of cycles of life expected from a cannon, crack initiation occurs relatively quickly. The transformation from the heat-check initiation of cracks to the start of fatigue crack growth can be seen in Figure 3. Many areas of crack initiation at the inner radius have linked together to form a continuous fatigue crack along the entire length of the section of the tube shown in the photo. Growth of fatigue cracks in cannons is considered next.

Fatigue Crack Growth

For those who doubt that fatigue cracks are generally present in cannons, consider Figure 4.[7] This polished and etched cross section of a tube shows that many fatigue cracks can be present. Two cracks appear at nearly every

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[7]Underwood, J. H. and Throop, J. F., "Surface Crack K-Estimates and Fatigue Life Calculations in Cannon Tubes," Part-Through Crack Fatigue Life Prediction, ASTM STP 687, J. B. Chang, Ed., American Society for Testing and Materials, 1979, pp. 195-210.

*This is the axial direction in the tube.

rifling land, with the longer of the two cracks nearly always from the side on which side loading is applied to the land by the projectile. The point here is that because of weight limitations, cannon tubes have stresses high enough that fatigue cracks can grow, once they are initiated at the inner radius.

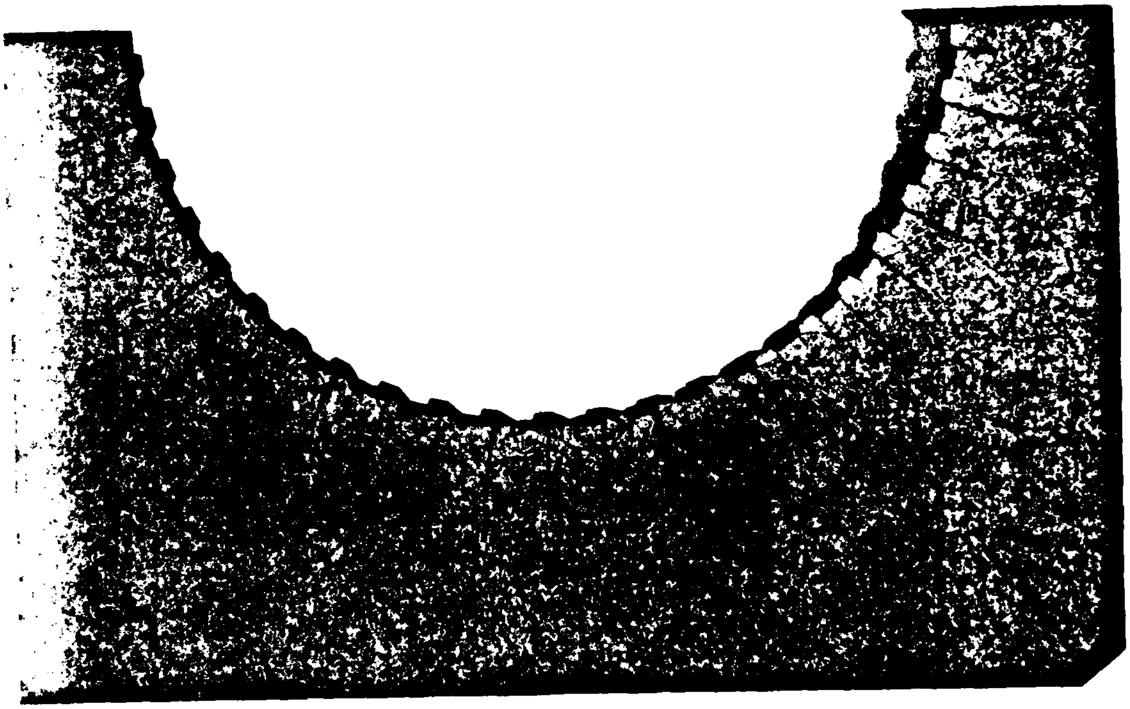

Figure 4. Polished and etched cross-section of cannon tube after fatigue loading; from Reference 7.

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[7]Underwood, J. H. and Throop, J. F., "Surface Crack K-Estimates and Fatigue Life Calculations in Cannon Tubes," Part-Through Crack Fatigue Life Prediction, ASTM STP 687, J. B. Chang, Ed., American Society for Testing and Materials, 1979, pp. 195-210.

The growth of fatigue cracks is typically in semi-elliptical shape, see again Figure 3. A nearly semi-circular shape is preferred with a shape factor $a/2c = 0.5$. However, as in Figure 3, the crack initiates along a considerable length of the tube due to interconnected heat-check cracks or rifling, so a semi-elliptical shape with $a/2c$ much less than 0.5 is typical. The crack grows progressively faster as it approaches the outer radius, and the crack growth for the last few cycles can sometimes be seen with the unaided eye, as in Figure 3. The very last cycle is a fast break-through to the outer radius, the top of Figure 3. This will be discussed later.

The factors which control the rate of fatigue crack growth per cycle in cannon tubes have been investigated by the late J. F. Throop.[9-11] The well known expressions for stress and stress intensity factor in a thick-wall cylinder can be used to determine the rate of fatigue crack growth in cylinders with idealized loading and geometry. It is the contributions of complex residual stresses and variable crack geometries that Throop investigated, primarily by experiments with full size cannon tubes.

Residual stresses are now routinely imparted to cannon tubes in order to prevent or at least slow the cracking which can occur, see again Figure 4.

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[9] Throop, J. F., Underwood, J. H., and Leger, G. S., "Thermal Relaxation in Autofrettaged Cylinders," Residual Stress and Stress Relaxation, Sagamore Army Materials Research Conference Proceedings, 28th, E. Kula and V. Weiss, Eds., Plenum Press, New York, 1982, pp. 205-226.

[10] Parker, A. P., Underwood, J. H., Throop, J. F., and Andrasic, C. P., "Stress Intensity and Fatigue Crack Growth in a Pressurized, Autofrettaged Thick Cylinder," Fracture Mechanics: Fourteenth Symposium, ASTM STP 791, American Society for Testing and Materials, 1983.

[11] Davidson, T. E. and Throop, J. F., "Practical Fracture Mechanics Applications to Design of High Pressure Vessels," Application of Fracture Mechanics to Design, J. J. Burke and V. Weiss, Eds., Plenum Publishing, New York, 1979, pp. 111-138.

The residual stresses are produced by loading the tube using internal pressure or an internal, oversized mandrel to a point where some or all of the tube wall is above the yield strain of the steel. This overstrain results in a distribution[9] of both compressive and tensile residual stresses in the tube. Such distributions for three amounts of overstrain are shown in Figure 5. The stress is that in the circumferential direction, which is normal to the plane of dominant cracking in cannon tubes and is therefore of primary concern. The r_1, r_2, and W are inner radius, outer radius, and wall thickness, respectively. A partial overstrain, such as 30 percent, is the situation in which yielding has occurred from the inner radius out to a point 30 percent through the wall thickness. The results of full scale fatigue life tests[10] of tubes with residual stress distributions as indicated in Figure 5 are shown in Figure 6. These tests are a direct measure of residual stress effects on tube life, and they are guidance to analysts for incorporating some complex and uncertain factors into their estimates of fatigue life. For example, a critical uncertainty in fatigue life analysis is the effect of nonideal yielding which is known to occur in high strength steels and is not included in idealized residual stress distributions such as Figure 5.

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[9] Throop, J. F., Underwood, J. H., and Leger, G. S., "Thermal Relaxation in Autofrettaged Cylinders," Residual Stress and Stress Relaxation, Sagamore Army Materials Research Conference Proceedings, 28th, E, Kula and V. Weiss, Eds., Plenum Press, New York, 1982, pp. 205-226.

[10] Parker, A. P., Underwood, J. H., Throop, J. F., and Andrasic, C. P., "Stress Intensity and Fatigue Crack Growth in a Pressurized, Autofrettaged Thick Cylinder," Fracture Mechanics: Fourteenth Symposium, ASTM STP 791, American Society for Testing and Materials, 1983.

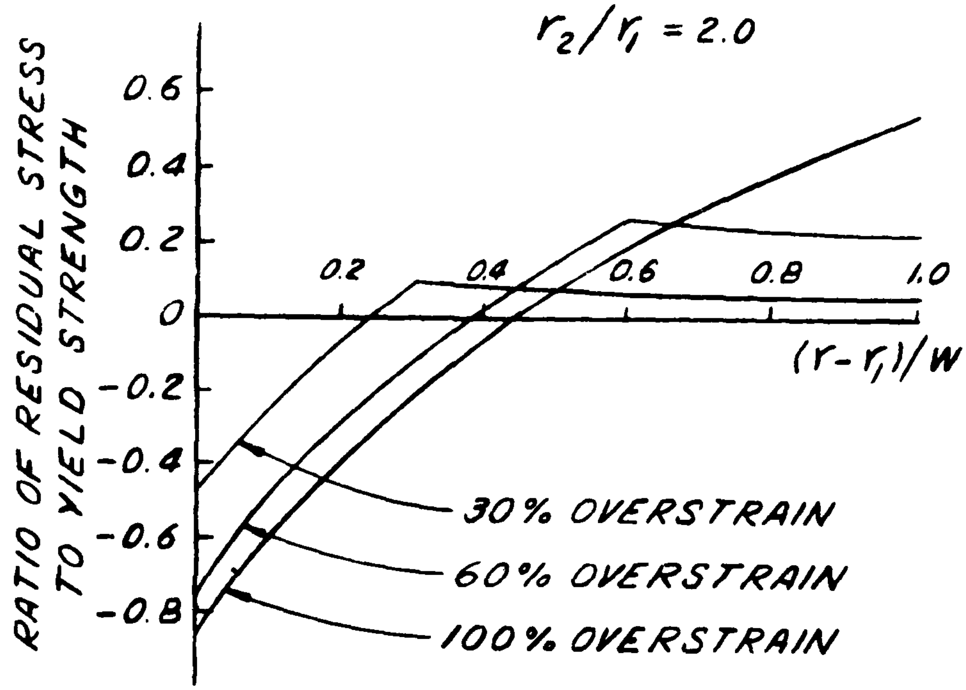

Figure 5. Circumferential residual stress due to overstrain relative to yield strength versus relative position in tube wall; von Mises' yield criterion; elastic-perfectly plastic material properties.

The experiments summarized in Figure 6 used cannon tubes in which a 6.4 mm deep semi-circular notch was electric-discharge machined at the inner radius. During pressure cycling the growth of the crack was measured by an ultrasonic method until final break-through of the 90.7 mm thick tube wall. For all tests the crack shape remained close to a semi-circle, a/2c = 0.5. The results show a significant increase in life due to a relatively small amount of overstrain, 30 percent, and a smaller increase in life for 60 percent overstrain. This indication of a diminishing return on increase in

life may be due to the similar trend of the residual compressive stress at the inner radius, see again Figure 5. In addition, the nonideal yielding mentioned above could contribute to the diminishing increase in fatigue life with increase in overstrain. Higher overstrain involves more yielding and thus more opportunity for nonideal effects.

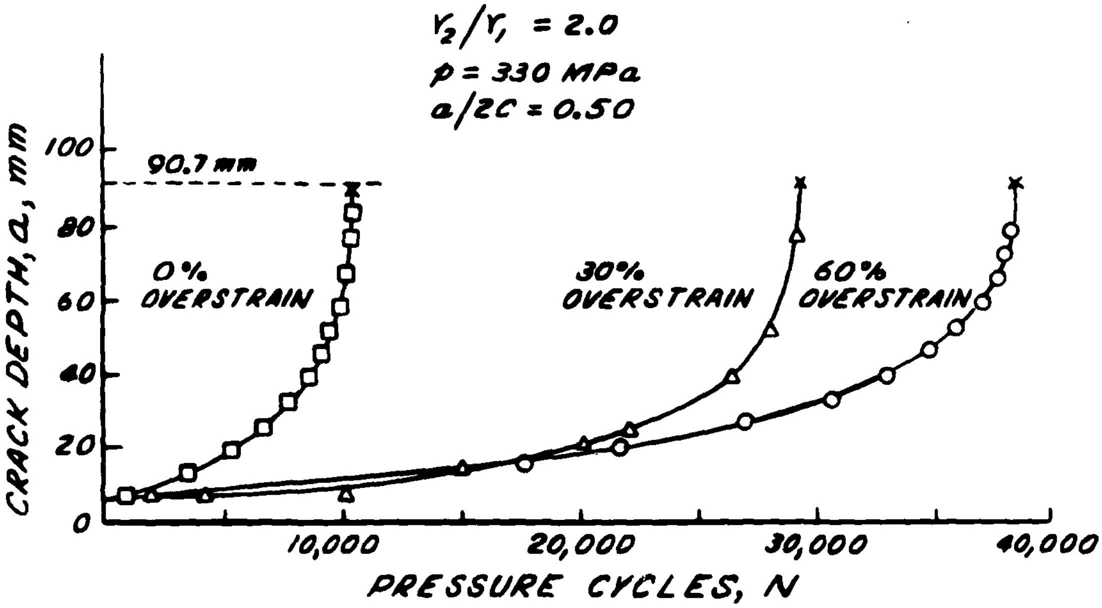

Figure 6. Fatigue crack depth versus number of pressure cycles for overstrained thick-wall cylinders; A723 steel, 1175 MPa yield strength; from Reference 10.

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[10] Parker, A. P., Underwood, J. H., Throop, J. F., and Andrasic, C. P., "Stress Intensity and Fatigue Crack Growth in a Pressurized, Autofrettaged Thick Cylinder," Fracture Mechanics: Fourteenth Symposium, ASTM STP 791, American Society for Testing and Materials, 1983.

Another important controlling factor for fatigue crack growth in cannon (and in any component) is the shape of the crack. Figure 7 summarizes other work of Throop[11] which shows the effect of crack shape from one extreme, a semi-circular crack with $a/2c = 0.5$, to near the other extreme, a very long, straight-fronted crack with $a/2c \rightarrow 0$. The values of $(a/2c)_o$ shown in Figure 7 are the starting values associated with electric-discharge machined, 6.4 mm deep notches in the cylinders. The cylinder with $a/2c = 0.5$ is the same as that in Figure 6. A cylinder with a $2c = 102$ mm long notch was tested, indicated by $(a/2c)_o = 0.062$. Two cylinders with a $2c = 508$ mm long notch were tested, indicated by $(a/2c)_o = 0.012$. Note that for the nearly straight-fronted crack, with $(a/2c)_o = 0.062$, the fatigue life was nearly ten times shorter than for the semi-circular crack. This demonstrates that the initiation of a crack over a considerable surface length will significantly reduce fatigue life over that for single point initiation. In addition to decreasing fatigue life, the straight-fronted crack will also favor a fast final failure. Note that for the two tubes with nearly straight-fronted cracks, final failure occurred at a crack depth of about 40 mm, rather than very near the tube outer surface at $a = 90.7$ mm, as for all the other tubes in Figures 6 and 7.

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[11] Davidson, T. E. and Throop, J. F., "Practical Fracture Mechanics Applications to Design of High Pressure Vessels," Application of Fracture Mechanics to Design, J. J. Burke and V. Weiss, Eds., Plenum Publishing, New York, 1979, pp. 111-138.

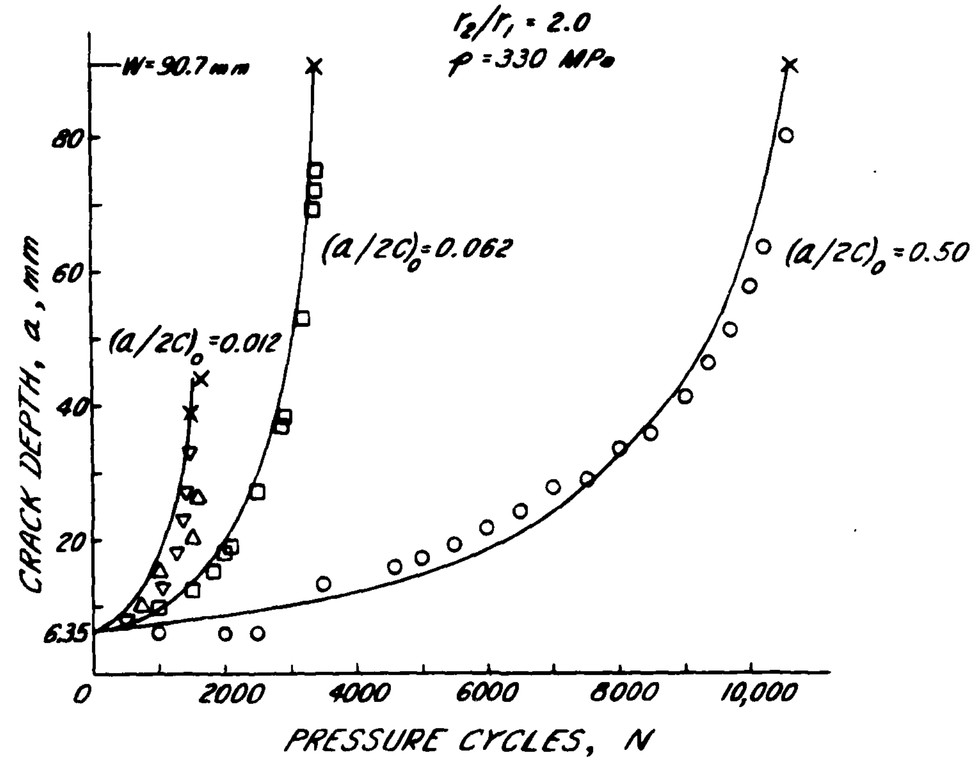

Figure 7. Fatigue crack depth versus number of pressure cycles for thick-wall cylinders with cracks of various shapes; A723 steel, 1175 MPa yield strength; from Reference 11.

The basic cause of the lower resistance to both fatigue crack growth and fast crack growth for longer surface cracks is the higher value of stress intensity factor. Recent work by Newman[4] gives general purpose expressions (based on three dimensional finite element analyses) for calculating stress intensity factors for cracks with a wide range of depth to surface length ratio. The expressions apply for finite thickness geometries under both

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[4]Newman, J. C. and Raju, I. S., "Analysis of Surface Cracks in Finite Plate Under Tension or Bending Loads," NASA TP 1578, National Aeronautics and Space Administration, 1979.

[11]Davidson, T. E. and Throop, J. F., "Practical Fracture Mechanics Applications to Design of High Pressure Vessels," Application of Fracture Mechanics to Design, J. J. Burke and V. Weiss, Eds., Plenum Publishing, New York, 1979, pp. 111-138.

tension and bending loading. These expressions can be used for a component, such as a cannon, which has loading which can be well described by a combination of bending and tension loading. With this stress intensity factor information and results such as in Figure 7, accurate descriptions of fatigue crack growth due to service loading can be made for cannon components.

Fast Crack Growth

A very common consideration with fast crack growth of cannon components is the effect of the relatively high time rate of loading. The rate effect is of most concern during the final fast growth of a crack out to the outer radius of the cylinder. Some of the first work on rate effects on the yield and fracture of cannon steels was performed by Kendall.[12,13] Some of his results are summarized in Figures 8 and 9. Figure 8 shows a quite gradual increase in yield strength over five orders of magnitude of elastic strain rate. The strain rate in a typical cannon firing is about 1.0 s^{-1}*, based on a typical yield strain for the material of 0.005 and a time from zero to maximum pressure in a cannon of 0.005 s. Comparing the strength at 1.0 s^{-1} strain rate, 1130 MPa, with that at 10^{-3} s^{-1} strain rate (for a typical static test), 1095 MPa, shows that loading rate has little effect on yield strength. Figure 9 summarizes effects of loading rate and temperature on the fracture

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[12]Kendall, D. P. and Davidson, T. E., "The Effect of Strain Rate on Yielding in High Strength Steels," Journal of Basic Engineering, Vol. 88, 1963, pp. 37-44.

[13]Kendall, D. P., "The Effect of Loading Rate and Temperature on the Fracture Toughness of High Strength Steels," Materials Research and Standards, Vol. 10, 1970.

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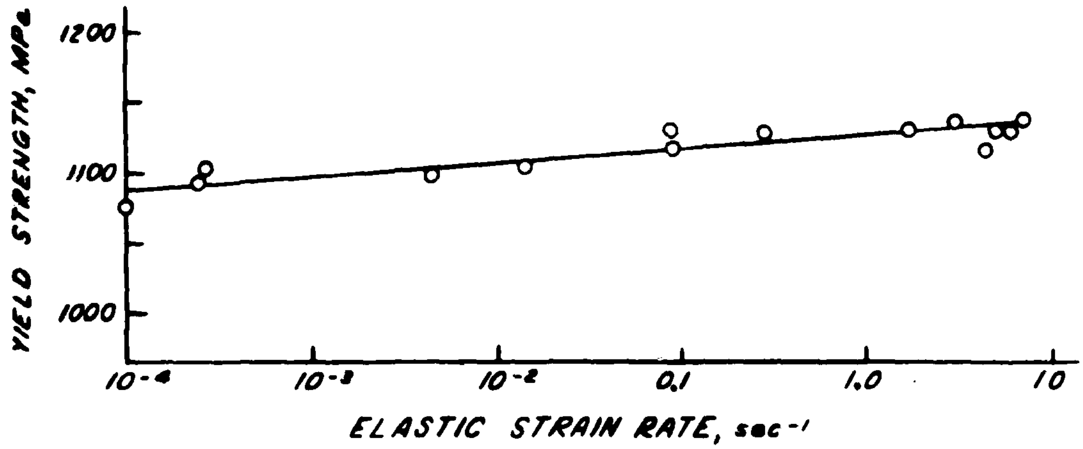

Figure 8. Yield strength versus elastic strain rate applied during yielding; AISI 4340 steel, longitudinal direction; from Reference 12.

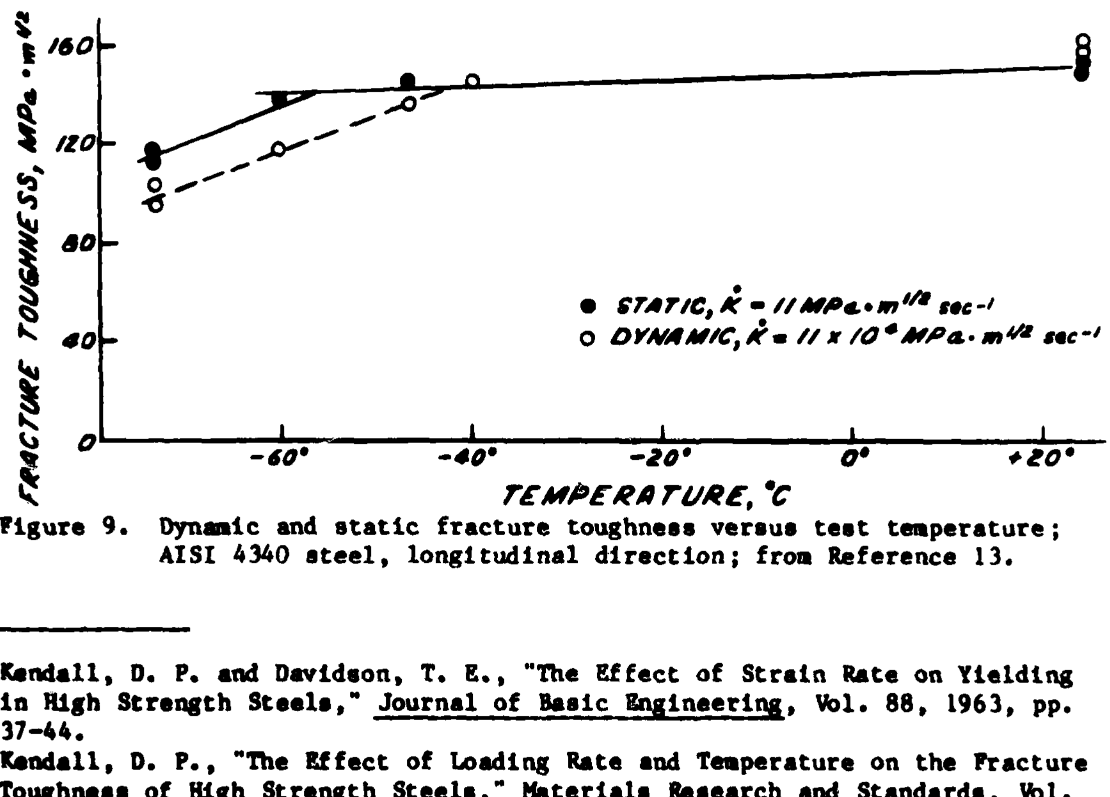

Figure 9. Dynamic and static fracture toughness versus test temperature; AISI 4340 steel, longitudinal direction; from Reference 13.

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[12]Kendall, D. P. and Davidson, T. E., "The Effect of Strain Rate on Yielding in High Strength Steels," Journal of Basic Engineering, Vol. 88, 1963, pp. 37-44.

[13]Kendall, D. P., "The Effect of Loading Rate and Temperature on the Fracture Toughness of High Strength Steels," Materials Research and Standards, Vol. 10, 1970.

toughness of a cannon steel. Over a wide range of temperature, which includes the service temperatures of cannon, no significant difference between static and dynamic fracture toughness was seen. However, it should be noted that the toughness of the material tested was within the expected range for good quality material; for lower toughness materials adverse effects on toughness by both low temperatures and high loading rates may be observed.

Fast crack growth of any component is more controlled by the material fracture toughness than by anything else. The most direct effect is seen in the critical crack size required for fast fracture. Calculations of critical crack size can be made from expressions such as Eq. (1). Each such expression applies only for a particular geometry, loading, and so forth. A common feature which can be obtained for nearly all cases is

$$a_c = \text{constant } (K_{Ic})^2 \tag{3}$$

so that a given change in fracture toughness, K_{Ic}, has a larger (to the power 2) effect on a_c. For example, from Figure 2, for a reduction in yield strength from 1300 to 1100 MPa, the expected (linear regression) fracture toughness would increase from 128 to 185 $MPa{\cdot}m^{1/2}$, a factor of 1.45, and the associated critical crack size would increase by a factor of 2.09, see Table I.

TABLE I. EFFECT OF YIELD STRENGTH ON FRACTURE TOUGHNESS, CRITICAL CRACK SIZE, AND SECTION SIZE REQUIRED FOR FAST FRACTURE

Yield Strength	Fracture Toughness From Figure 2	Ratio of:			
σ_{ys} MPa	K_{Ic} $MPa{\cdot}m^{1/2}$	σ_{ys}	K_{Ic}	a_c	section size
1100	185	0.85	1.45	2.09	2.92
1300	128				

Another less direct but equally important effect of fracture toughness on fast crack growth is related to the section size around the crack which is required in order for a fast fracture to occur. In simplified concept, if the distance ahead of a crack and along the crack front is too small, then the plastic deformation around the crack will serve to prevent fast crack growth. The expression for the size which is required for a fast fracture is:

$$\text{size} = \text{constant}\ (K_{Ic}/\sigma_{ys})^2 \qquad (4)$$

The material yield strength, σ_{ys}, has an effect in combination with the K_{Ic} effect. Expressions such as Eq. (4) are used to calculate the required size of K_{Ic} test specimens for a proper (sufficiently brittle) test and also to calculate the plastic zone size around a crack. The implications of Eq. (4) with regard to cannons are shown in Table I. Note that for a 15 percent decrease in yield strength, there is a corresponding increase of nearly 200 percent in the section size for which a fast, brittle failure would be retarded. This effect has direct application to the important final failure mode of a cannon, such as shown in the fracture surface of Figure 3. By incorporating a modest decrease in the yield strength, the likelihood of a safe, final break-through of a fatigue crack to the outer radius of the cannon tube (top of the photo in Figure 3) is greatly increased. It is the increased yielding around the crack which effectively unloads a larger area around the crack. This leads to the safe, leak-before-break final failure of the cannon tube which is now a basic part of cannon design.

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